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A DETERMINATION OF THE TEMPERATURE FIELD AND THE  
HEAT LOSSES IN THE INSULATION BARRIER OF COM-  
PRESSED-GAS TANKS

By

S. M. Rips



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## UNEDITED ROUGH DRAFT TRANSLATION

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PRESSED-GAS TANKS

By: S. M. Rips

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A DETERMINATION OF THE TEMPERATURE FIELD  
AND THE HEAT LOSSES IN THE INSULATION  
BARRIER OF COMPRESSED-GAS TANKS

S. M. Rips

Tanks are widely employed for the storage and long-distance transportation of large quantities of compressed gases (oxygen, nitrogen, ammonia, hydrocarbons, etc.). The crux and also the complexity of the problem of their storage and transportation lie in the fact that the existence of the liquid phase of the gases during transportation depends upon the possibility of maintaining a low (negative), and at times an extremely low (deep) temperature, such as for oxygen ( $-183^{\circ}$ ) and nitrogen ( $-196^{\circ}$ ). In the near future the problem of transporting and storing liquid hydrogen ( $-252^{\circ}$ ) will acquire practical importance. The advantage in the use of large capacities is due, on the one hand, to the relatively low cold losses, and, on the other hand, to the favorable variation of these losses with time. Both of these depend upon the proper choice of the material, dimensions, and design of the insulation barrier. In the present article, on the basis of an investigation of the temperature field in various types of insulation, the heat flows (cold losses) are determined both during the

cooling of the tank insulation (nonsteady state), as well as after the temperature field has been established, and illustrative examples are given of the calculation for liquid oxygen, nitrogen, and hydrogen. The proposed method of calculation can be successfully applied to insulation barriers for any other compressed gases.

Insulation-cooling Stage. The amount of heat lost by an element of the insulation barrier (Fig. 1) is determined as the algebraic sum of the incoming ( $Q_1$ ) and outgoing ( $Q_2$ ) heat<sup>1</sup>:

$$Q_1 + Q_2 = \frac{-\lambda \Delta \varphi L \Delta \tau}{\Delta R} \left[ (t - t_{in}) \left( R - \frac{\Delta R}{2} \right) + (t - t_{ex}) \left( R + \frac{\Delta R}{2} \right) \right] \quad (1)$$

where  $\lambda$  — is the coefficient of thermal conductivity of the insulation, kcal/m·hr·°C;

$\Delta \varphi$  — is the angle bounding the element to be calculated;

$L$  — is the length of the calculation element, m;

$\Delta R$  — is the thickness of the element, m;

$R$  — is the mean radius of the element, m;

$t$  — is the temperature at a desired point in the element, °C;

$t_{in}$ ,  $t_{ex}$  — are the internal and external temperatures of the element, °C;

and  $\Delta \tau$  — is a period of time (in sequence).

The loss of this amount of heat causes a decrease in the temperature of the element by an amount determined by the heat-balance equation

$$Q_1 + Q_2 = c \gamma (t_{\tau+\Delta\tau} - t) \Delta V = \Delta Q_c (t_{\tau+\Delta\tau} - t) \quad (2)$$

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<sup>1</sup>S. M. Rips. Khimicheskaya Promyshlennost', No. 4, 228, 1955.

where  $\Delta V$  — is the volume of the element under consideration,  $m^3$ ;

$c$  — is the specific heat of the element material,  $kcal/kg \cdot ^\circ C$ ;

$\Delta g$  — is the weight of the element,  $kg$ ;

$\gamma$  — is the specific gravity of the element material,  $kg/m^3$ ;

$t_{\tau+\Delta\tau}$  — is the temperature at the point of calculation after time  $\Delta\tau$ ,  $^\circ C$ .

Equating the right sides of Eqs. (1) and (2) and transposing terms, we find the temperature at the center of the layer at time  $\tau + \Delta\tau$

$$t_{\tau+\Delta\tau} = \left[ 1 - 2 \frac{\alpha \Delta\tau}{\Delta R^2} \right] t + \frac{\alpha \Delta\tau}{\Delta R^2} \left( 1 - \frac{\Delta R}{2R} \right) t_{in} + \frac{\alpha \Delta\tau}{\Delta R^2} \left( 1 + \frac{\Delta R}{2R} \right) t_{ex} \quad (3)$$

where  $\alpha = \lambda/c\gamma$  is the coefficient of thermal diffusivity,  $m^2/hr$ .

The limit of applicability of Eq. (3) is the maximum time  $\Delta\tau_{max}$  at which the steady-state temperature of the layer ceases to depend on the initial temperature of the layer  $t$ , i.e., when the coefficient of  $t$  becomes equal to zero

$$1 - 2 \cdot \frac{\alpha \Delta\tau}{\Delta R^2} = 0 \quad (4)$$

Hence

$$\Delta\tau_{max} = \frac{\Delta R^2}{2\alpha} \quad (5)$$

Therefore, when  $\Delta\tau = \Delta\tau_{max}$ , the equation for the calculation assumes the following form

$$t_{\tau+\Delta\tau} = \frac{\alpha \Delta\tau_{max}}{\Delta R^2} \left( 1 - \frac{\Delta R}{2R} \right) t_{in} + \frac{\alpha \Delta\tau_{max}}{\Delta R^2} \left( 1 + \frac{\Delta R}{2R} \right) t_{ex}$$

Substituting the value for  $\Delta\tau_{max}$  into Eq.(3), we obtain

$$t_{\tau+\Delta\tau} = \frac{1}{2} \left( 1 - \frac{\Delta R}{2R} \right) t_{in} + \frac{1}{2} \left( 1 + \frac{\Delta R}{2R} \right) t_{ex} \quad (6)$$

From Eq. (6) the steady-state temperature of a layer of insulation can be determined according to the time lapse  $n\Delta\tau_{max}$ , if the

temperatures of the neighboring layers are known.

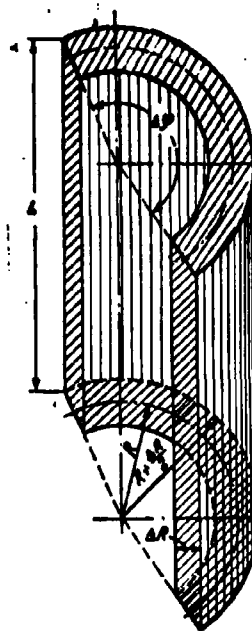


Fig. 1. Diagram of insulation-barrier element.

The initial data for the use of Eq. (6) are, obviously, the initial temperature distribution and the prescribed boundary conditions, for which the calculation of the temperature field should be carried out successively for the time intervals  $\Delta\tau_{\max}$ .

Knowing the temperature field, it is possible to calculate the amount of heat entering from the outside, then given off or accumulated by the insulation and transmitted through it to the inside of the tank. The order of calculation is illustrated below with the aid of numerical examples for different types of insulation.

Steady-state Stage. For the steady state the initial equation for the temperature field in the tank will be the following:

$$t_{st} = \frac{t_{in} \frac{\log R_{ex}}{R} + t_{ex} \frac{\log R}{R_{in}}}{\log \frac{R_{ex}}{R_{in}}} \quad (7)$$



The amount of heat passing through the insulation of the cylindrical portion during the steady state will be determined by the formula

$$Q_{st} = \frac{2\pi\lambda L}{2.3 \lg \frac{R_{ex}}{R_{in}}} (t_{in} - t_{ex}) \text{ kcal/hr} \quad (8)$$

For the spherical ends of the tank we have

$$t_{st} = \frac{t_{ex} R_{ex} - t_{in} R_{in}}{R_{ex} - R_{in}} + \frac{(t_{in} - t_{ex}) R_{ex} R_{in}}{R_{ex} - R_{in}} \frac{1}{R} \quad (9)$$

$$Q_{st} = 4\pi\lambda (t_{ex} - t_{in}) \frac{R_{ex} R_{in}}{\Delta R} \text{ kcal/hr} \quad (10)$$

### Examples

We shall give as an example the calculation of the temperature field for an 11,200 liter tank which corresponds to ~ 12.75 metric tons of liquid oxygen, ~ 9.072 metric tons of liquid nitrogen, and ~ 784 kg of liquid hydrogen. In the calculation we have taken (Fig. 2) (mm):

Inner diameter of brass vessel of tank, $D = 2R$ .....	2,100
Outer diameter of brass vessel of tank (same as inner diameter of insulation) $D_B = 2R_B = 2R_1$ .....	2,105
Wall thickness of brass vessel .....	2.5
Outer diameter of insulation (same as inner diameter of casing) $D_H = 2R_H = 2R_{21}$ .....	2,805
Insulation thickness $\delta = \Sigma \Delta R$ .....	350
Outer diameter of casing $D_K = 2R_{22}$ .....	2,820
Radius of spherical bottoms of tank $R$ .....	1,050
Length of cylindrical portion of tank $L$ .....	2,100
Overall length of brass vessel $L_P$ .....	4,205
Length of tank casing $L_K$ .....	5,605

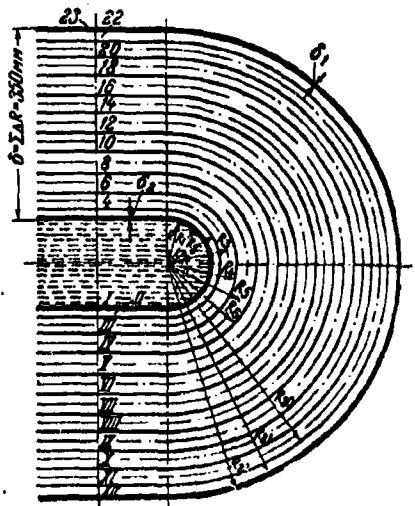


Fig.2. Diagram for calculation of temperature field.

The number of insulation layers is taken equal to 10. The accuracy of the solution is quite satisfactory with this number, as indicated by previous calculations. In accordance with the requirements of the method of "finite differences", a half-space each was left at the surfaces of the brass vessel and casing. The width of a layer will then be

$$\Delta R = \frac{\delta}{10} = \frac{350}{10} = 35 \text{ mm}$$

We shall consider the cylindrical and spherical portions of the tank separately.

#### Temperature Field in the Insulation in the Cylindrical Portion of the Tank

Insulation-cooling Stage. For the calculation of the temperature field of the insulation during cooling we shall make use of the equation which we have derived (6). By substituting into it the geometric dimensions of each layer we obtain the values listed in Table 1.

Table 1  
Geometrical Characteristics of the Layers of Insulation

No. of layer	No. of point	R, mm	$\frac{\Delta R}{2R}$	$1 - \frac{\Delta R}{2R}$	$1 + \frac{\Delta R}{2R}$	$\frac{\Delta R}{R}$	$1 - \frac{\Delta R}{R}$	$1 + \frac{\Delta R}{R}$
III	4	1087,5	0,0160	0,9840	0,0160	0,0320	0,9680	1,0320
IV	6	1122,5	0,0156	0,9844	0,0156	0,0312	0,9688	1,0312
V	8	1157,5	0,0151	0,9849	0,0151	0,0302	0,9698	1,0302
VI	10	1192,5	0,0146	0,9854	0,0146	0,0292	0,9708	1,0292
VII	12	1227,5	0,0142	0,9858	0,0142	0,0284	0,9716	1,0284
VIII	14	1262,5	0,0138	0,9862	0,0138	0,0276	0,9724	1,0276
IX	16	1297,5	0,0135	0,9865	0,0135	0,0270	0,9730	1,0270
X	18	1332,5	0,0131	0,9869	0,0131	0,0262	0,9738	1,0262
XI	20	1367,5	0,0128	0,9872	0,0128	0,0256	0,9746	1,0256

Calculations using Eq. (6) have shown that for purposes of simplification the following general equation with mean values for the coefficients of  $t_{in}$  and  $t_{ex}$  may be used for all the insulation layers without any special error

$$t = 0,493 t_{in} + 0,507 t_{ex} \quad (11)$$

The results of a calculation of the temperature field for hydrogen using this equation are given in Table 2 and Fig. 3. The results of similar calculations for oxygen and nitrogen are given in Fig. 4.

Table 2  
Temperature Field in the Cylindrical Portion of the  
Insulation of a Hydrogen Tank

nΔr	$t_2$	$t_4$	$t_6$	$t_8$	$t_{10}$	$t_{12}$	$t_{14}$	$t_{16}$	$t_{18}$	$t_{20}$	$t_{22}$
0	-252,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0
1	-252,0	-114,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0
2	-252,0	-114,0	-46,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0
3	-252,0	-147,0	-46,0	-13,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0
4	-252,0	-147,0	-79,0	-13,0	+4,0	+20,0	+20,0	+20,0	+20,0	+20,0	+20,0
5	-252,0	-164,0	-79,0	-37,0	+4,0	+12,0	+20,0	+20,0	+20,0	+20,0	+20,0
10	-252,0	-181,0	-124,0	-69,0	-38,0	-8,0	+4,0	+15,0	+18,0	+20,0	+20,0
20	-252,0	-200,0	-154,1	-110,0	-77,4	-45,8	-29,1	-13,0	0,0	+13,0	+20,0
30	-252,0	-209,1	-170,1	-132,2	-100,9	-70,4	-48,4	-27,0	-10,3	+5,9	+20,0
40	-252,0	-213,4	-177,7	-143,1	-113,1	-83,8	-59,7	-36,4	-16,7	+2,4	+20,0
50	-252,0	-216,3	-182,8	-150,4	-121,0	-92,5	-68,2	-42,8	-21,0	+0,2	+20,0
60	-252,0	-218,1	-186,1	-155,0	-125,7	-98,9	-72,1	-47,0	-24,0	-1,1	+20,0
70	-252,0	-219,2	-187,9	-157,6	-128,9	-101,0	-74,9	-49,5	-25,6	-2,4	+20,0
80	-252,0	-219,7	-189,0	-159,2	-130,5	-102,7	-76,3	-50,8	-26,5	-2,8	+20,0
90	-252,0	-220,2	-189,5	-159,9	-131,5	-103,9	-77,4	-51,7	-27,0	-3,1	+20,0
100	-252,0	-220,7	-190,0	-160,9	-131,8	-104,9	-78,4	-52,2	-27,4	-3,3	+20,0
110	-252,0	-221,2	-190,5	-161,9	-132,15	-105,9	-79,4	-52,7	-27,6	-3,35	+20,0
120	-252,0	-221,5	-191,0	-162,8	-132,3	-107,0	-80,1	-53,1	-27,8	-3,36	+20,0
Steady state	-252,0	-221,5	-191,0	-162,8	-132,3	-108,8	-80,1	-53,1	-27,8	-3,36	+20,0

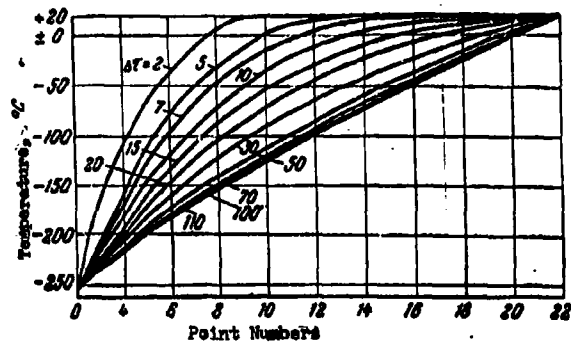


Fig. 3. The temperature field across the thickness of the insulation (cylindrical portion of a hydrogen tank).

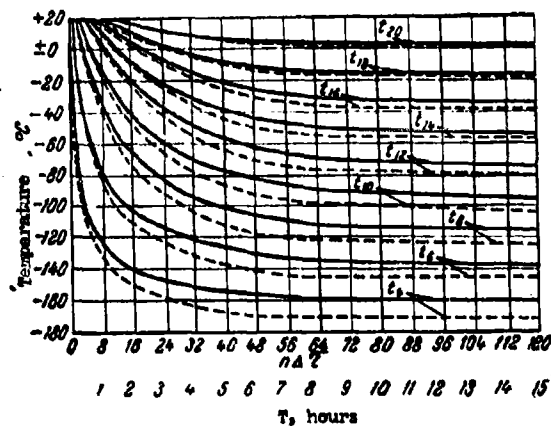


Fig. 4. Temperature field across the thickness of the insulation (cylindrical portion of oxygen and nitrogen tank; lower abscissa ( $\tau$ ) pertains to mpor): dotted lines-nitrogen tank; solid lines - oxygen tank.

The following assumptions were made in the calculation:

the temperatures of the inner and outer surfaces of the wall of the brass vessel were assumed to be constant and equal to the temperature of the compressed gas ( $t_{liq. H_2} = -252^\circ$ ;  $t_{liq. O_2} = -183^\circ$ ;  $t_{liq. N_2} = -196^\circ$ );

the temperature of the inner and outer surfaces of the casing walls (points 22 and 23, Fig. 2) were also assumed to be constant and equal to +20°;

it was assumed that the tank was completely filled with liquid gas;

there were no thermal bridges in the tank (i.e., metallic fastening elements joining the vessel with the casing).

An analysis of the curves and tables shows that further cooling of the insulation practically stops after an elapsed time of (100 - 120)  $\Delta\tau_{\max}$  for  $H_2$ ; (90-110)  $\Delta\tau_{\max}$  for  $O_2$  and (110-120)  $\Delta\tau_{\max}$  for  $N_2$ , and after this the temperature field becomes steady.

From the formulas for the calculation it is apparent that the temperature distribution in the tank insulation depends only on the quantity  $\Delta\tau_{\max}$ , which is, in turn, directly related to the physical characteristics and thickness of the insulation layer

$$\Delta\tau_{\max} = \frac{\Delta R^2}{2a} = \frac{\Delta R^2 c \gamma}{2\lambda}$$

Values of  $\Delta\tau_{\max}$  for different types of insulation, when the thickness of one layer of insulation is 35 mm, are listed in Table 3.

Table 3  
Values of  $\Delta\tau_{\max}$  for Different Types of Insulation

Insulating material	$\gamma$ kg/m <sup>3</sup>	$c$ kcal/kg <sup>o</sup>	$\lambda$ kcal/m <sup>o</sup> ·cm·hr	$a \cdot 10^8$ m <sup>2</sup> /hr	$\Delta\tau_{\max}$ hr
Magnesia . . .	240	0,2	0,030	0,625	0,98
Magnesia . . .	400	0,2	0,065	0,813	0,754
Nipor . . .	25	0,24	0,030	5	0,1225
Aerogel . . .	100	0,2	0,012	0,61	1,004
Mineral wool	250	0,2	0,060	1,2	0,51
Pearlite . . .	90	0,2	0,029	1,61	0,381
(milled)					
Vacuum-layer screening . . .	80	0,2	$\sim 38 \cdot 10^{-6}$	$\sim 0,00237$	258
insulation*					

\* Chem. Eng., № 24 (1969).

From an examination of the data in Table 3 it follows that magnesia ( $\gamma = 240$ ) and aerogel provide identical temperature fields within about the same time. With mineral wool the cooling process is shortened by almost half, while for mior it is almost eight times shorter in comparison with aerogel; in other words, if the steady-state temperature field for mineral wool is attained, for example, after 50 to 60 hrs, then for mior this regime will ensue within 12.5 - 13 hrs (Fig. 4).

Steady-state Stage. The results of a calculation of the temperatures in the insulation layers during steady state, using Eq. (7), are given in Table 4.

The agreement between the temperatures of the insulation layers obtained in the calculation for the insulation-cooling stage (last line in Table 2) with those obtained in the calculation for steady state is convincing verification of the correctness of the calculation of the temperature field.

#### Temperature Field for the Insulation in the Spherical Portion (Ends) of the Tank

Insulation-cooling Stage. For the calculation of the temperature field in the spherical ends we shall employ the following equation<sup>1</sup>:

$$t_{e+\Delta t} = \frac{1}{2} \left( 1 - \frac{\Delta R}{R} \right) t_{in} + \frac{1}{2} \left( 1 + \frac{\Delta R}{R} \right) t_{ex} \quad (12)$$

In substituting the geometrical dimensions of each layer into this equation (cf. Table 1), we may with sufficient accuracy take the mean value of the coefficients of  $t_{in}$  and  $t_{ex}$  equal to 0.486 and 0.514 respectively; then

$$t_{e+\Delta t} = 0.486 t_{in} + 0.514 t_{ex} \quad (13)$$

The results of calculating the temperature field for hydrogen with this equation are given in Figs. 5 and 6, and for oxygen and nitrogen in Fig. 7. It is apparent from the figures that the steady state ensues when  $\Delta\tau_{\max} = 80 - 100$  periods for  $O_2$  and  $N_2$ , and when  $\Delta\tau_{\max} = 90 - 110$  periods for  $H_2$ .

Table 4  
Number of Periods and Temperature of Layers Calculated  
with Eq. (7) for Steady State

Gas	Portion of Tank	$n_{st}$	$t_5$	$t_4$	$t_3$	$t_2$	$t_{10}$	$t_{11}$	$t_{12}$	$t_{13}$	$t_{14}$	$t_{15}$	$t_{16}$	$t_{17}$
$H_2$	Cylindrical	110	-252	-221.5	-191.0	-162.8	-132.3	-108.6	-80.1	-53.1	-27.8	-3.36	-20	
	Spherical	110	-252	-216.8	-184.1	-153.2	-124.1	-96.6	-70.7	-49.6	-23.0	-1.0	-20	
$O_2$	Cylindrical	110	-183	-160.0	-137.5	-110.0	-88.0	-73.3	-53.2	-33.8	-15.6	-2.2	-20	
	Spherical	100	-183	-157.4	-133.3	-110.0	-88.0	-67.0	-48.0	-29.0	-12.0	-4.0	-20	
$N_2$	Cylindrical	120	-196	-171.4	-147.47	-124.45	-102.1	-79.96	-59.1	-38.55	-18.45	+0.95	-20	
	Spherical	100	-196	-167.9	-141.7	-117.2	-94.1	-72.3	-51.8	-32.2	-13.7	-3.6	-20	

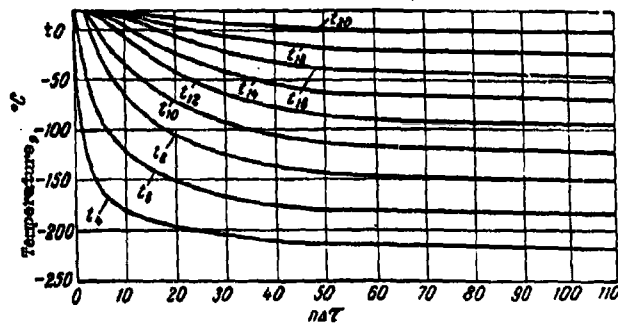


Fig. 5. Temperature field of a hydrogen tank (spherical portion).

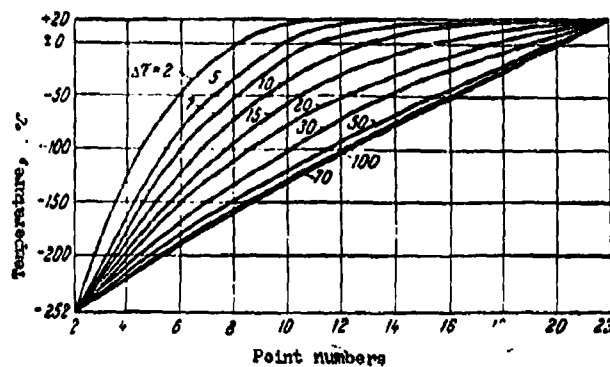


Fig. 6. Temperature field across the thickness of the insulation (spherical portion of hydrogen tank).



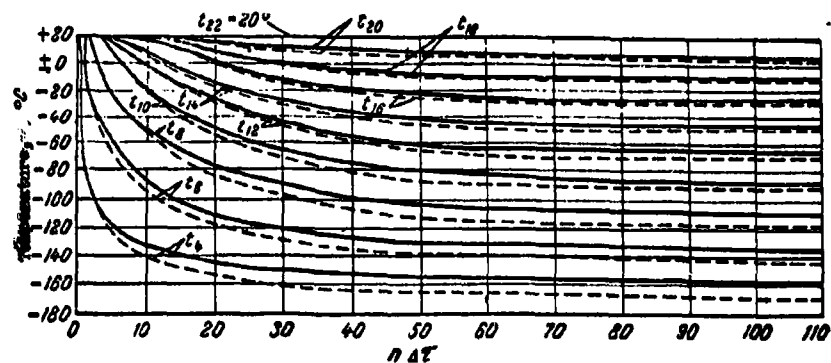


Fig. 7. Temperature field in the insulation (spherical portion of oxygen and nitrogen tanks; dotted lines - nitrogen tank; solid lines - oxygen tank).

Steady-state Stage. The temperature field during steady state can be determined from Eq. (9). After substituting into it the values for  $t_{in}$ ,  $t_{ex}$ ,  $R_B$  and  $R_H$  we obtain:

$$\text{for oxygen} \quad t = 630,5 - \frac{875}{R} \quad (14a)$$

$$\text{for nitrogen} \quad t = 669,5 - \frac{910,6}{R} \quad (14b)$$

$$\text{for hydrogen} \quad t = 838 - \frac{1145}{R} \quad (14c)$$

Substituting the values of  $R$  for the layers of insulation into the expression obtained, we find the temperatures of each layer (Table 4), which are nearly equal to the temperatures at the end of the insulation cooling.

#### Liquid Losses During the Filling of the Cylinder

The greatest amount of heat, and during a short interval of time at that, is fed into the liquid during the cooling of the brass (or aluminum) vessel in the process of filling and associated cooling

of the fastening elements, which are in contact with the volume, and of the inner half-layer of insulation.

If the weight of the fastening elements is taken to be 25% of the weight of the vessel, then the weight of the metal cooled from + 20° to the temperature of the liquid  $t_{liq.}$ , will be  $G_m = 740$  kg.

With a specific heat  $c_m = 0.082$  kcal/kg.°C for brass the amount of heat fed into the liquid will equal

$$Q_m = G_m c_m (20 + t_{liq.}) \quad (15)$$

for oxygen ..... 12300 kcal

for nitrogen ..... 13150 kcal

for hydrogen ..... 18500 kcal

In this case the weight of vaporized liquid amounts to ~ 246 kg  $O_2$ , almost as much  $N_2$ , and 168 kg  $H_2^*$ .

The amount of heat taken from the inner half-layer of insulation, while it is being cooled from + 20° to  $t_{liq.}$ , will be

$$\text{for oxygen } Q_{O_2} = (4\pi r^2 \cdot 0.0175 + 2\pi r L \times 0.0175) c_{\gamma} (20 + 183) = 75 c_{\gamma} \gamma_{ins} \quad (16a)$$

$$\text{for nitrogen } Q_{N_2} = 80 c_{\gamma} \gamma_{ins} \quad (16b)$$

$$\text{for hydrogen } Q_{H_2} = 100 c_{\gamma} \gamma_{ins} \quad (16c)$$

where  $c_{ins}$  and  $\gamma_{ins}$ —are the specific heat and specific gravity of the insulation;

$r$  — is the mean radius of the half-layer, m;

and 0.0175 — is the thickness of the half-layer, m.

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\*The latent heats were taken  $r_{O_2} = 51$  kcal/kg;  $r_{N_2} = 50$  kcal/kg;  $r_{H_2} = 110$  kcal/kg.

The results obtained from the calculation of the temperature fields permit us to ascertain the heat flows and, consequently, the losses of liquid in the tank in time.

Insulation-cooling Stage. The amount of heat entering the liquid due to cooling of the entire insulation (apart from the inner half-layer) during a certain time  $n\Delta\tau_{\max}$ , starting with the beginning of cooling, may be calculated from the decrease in the temperature of the insulation, proceeding on the basis of the temperature field, from the following equations:

for the cylindrical portion of the tank

$$Q_{\text{ins}}^{\text{cyl}} = 2\pi L c_{\text{ins}} \gamma_{\text{ins}} [R_4 \Delta R (20 - t_{n,4}) + R_6 \Delta R (20 - t_{n,6}) + \dots + R_{20} \Delta R (20 - t_{n,20})] = A_{\text{cyl}} c_{\text{ins}} \gamma_{\text{ins}} \quad (17)$$

for the spherical portion of the tank

$$Q_{\text{ins}}^{\text{sph}} = 4\pi c_{\text{ins}} \gamma_{\text{ins}} [R_4^2 \Delta R (20 - t_{n,4}^*) + R_6^2 \Delta R (20 - t_{n,6}^*) + \dots + R_{20}^2 \Delta R (20 - t_{n,20}^*)] = A_{\text{sph}} c_{\text{ins}} \gamma_{\text{ins}} \quad (18)$$

where  $A_{\text{cyl}}$  and  $A_{\text{sph}}$  are coefficients depending upon the dimensions of the tank and the temperatures of the insulation layers at the instant of time under consideration.

The temperatures are taken in accordance with the temperature field of the tank ( $t$ ) and sphere ( $t^*$ ).

For the tank as a whole we have

$$Q = Q_{\text{ins}}^{\text{cyl}} + Q_{\text{ins}}^{\text{sph}} + A_{\text{sph}} c_{\text{ins}} \gamma_{\text{ins}} = A_{\text{tank}} c_{\text{ins}} \gamma_{\text{ins}} \quad (19)$$

As the temperature of the outer insulation layers decreases, there also occurs an influx of heat from without, beginning at some moment of time  $m\Delta\tau_{\max}$ ; this influx increases as the steady state is approached.

Proceeding on the basis of the given temperature field pertaining to the outer insulation layers for the cylindrical and spherical

portions of the tank, it is possible to calculate that after some interval of time  $P$  has elapsed, the amount of heat passing through time  $\Delta\tau_{\max}$  will be through the outer layer from without during the

$$\Delta Q_p = \Delta Q_p^{\text{cyl}} + \Delta Q_p^{\text{sph}} = \frac{2\pi\lambda L}{2,31 \log \frac{R_{\text{ex}}}{R_{\text{in}}}} (t_{p-20} - t_{p-20}) \Delta\tau_{\max} +$$

$$+ 4\pi L \frac{R_{\text{ex}} R_{\text{in}}}{\Delta R} (t_{p-20} - t_{p-20}) \Delta\tau_{\max} \quad (20)$$

and since

$$\Delta\tau_{\max} = \frac{\Delta R^2 c \gamma}{2\lambda}$$

we obtain finally, after substituting the dimensions of the cylinder,

$$\Delta Q_p = \Delta Q_p^{\text{cyl}} + \Delta Q_p^{\text{sph}} = 0,32 \frac{\lambda L}{\log \frac{R_{\text{ex}}}{R_{\text{in}}}} (20 - t_{p-20}) +$$

$$+ 0,42 \frac{\lambda L R_{\text{ex}} R_{\text{in}}}{\Delta R} (20 - t_{p-20}) \quad (21)$$

If it is required to calculate the amount of heat entering from the outside during the period of time between  $m\Delta\tau_{\max}$  and  $n\Delta\tau_{\max}$ , then we must add up the amounts of heat for all periods of time in the given interval

$$Q_{\text{ex}} = B_{\text{tank}} c \gamma \tau_{\text{ins}} \quad (22)$$

where

$$B_{\text{tank}} = B_{\text{cyl}} + B_{\text{sph}} \quad (23a)$$

$$B_{\text{cyl}} = 0,32 \left[ (n-m) 20 - \sum_{m_1}^n t_{p-20} \right] \quad (23b)$$

$$B_{\text{sph}} = 0,42 \left[ (n-m) 20 - \sum_{m_1}^n t_{p-20} \right] \quad (23c)$$

The total amount of heat fed to the inner vessel may be found as the sum of heat drawn off from the insulation and the heat flowing in from without. For this purpose we may, using the temperature field found earlier, calculate the amount of heat passing through the inner layer of insulation during a time  $n\Delta\tau_{\max}$ .

$$Q_1 = \frac{\pi \Delta R^2 L}{2,31 \log \frac{R_{\text{ex}}}{R_{\text{in}}}} \frac{c \gamma \tau_{\text{ins}}}{2\lambda} \left( n t_{11q} - \sum_{1}^n t_{p-4} \right) +$$

$$+ 2\pi R_{\text{ex}} R_{\text{in}} \Delta R c \gamma \tau_{\text{ins}} \left( n t_{11q} - \sum_{1}^n t_{p-4} \right)$$

Substituting the geometrical dimensions of the cylinder, we obtain

$$Q_{in} \left[ 0.25 \left( n_{liq}^t - \sum_1^n t_{p-1} \right) + 0.252 \left( n_{liq}^c - \sum_1^n t_{p-1}^c \right) \right] \frac{q_{hs} \gamma_{ins}}{C_{tank} C_{ins} \gamma_{ins}} = \quad (24)$$

where  $C_{tank} = C_{cyl} + C_{sph}$  (25a)

$$C_{cyl} = 0.25 \left( n_{liq}^t - \sum_1^n t_{p-1} \right) \quad (25b)$$

$$C_{sph} = 0.252 \left( n_{liq}^c - \sum_1^n t_{p-1}^c \right) \quad (25c)$$

The computed values of the coefficients, A, B, and C in formulas (17), (18), (19), (22), and (24) for liquid hydrogen and various time intervals are given in Table 5. The slight deviation (about 2% on the average) in the calculation of the value of  $C_{tank} = C_{cyl} + C_{sph}$  and  $C_{tank} = A_{tank} + B_{tank}$ . (cf. last three columns in Table 5) confirms the accuracy of the calculations which we have carried out. These coefficients may be similarly calculated for any other medium.

An analysis of the data in Table 5 shows that the maximum influx of heat to the vessel is observed in the initial cooling stage. The intensity of the heat flow decreases in the course of time, as the steady state is approached, and becomes equal to the intensity of the influx of heat from without.

On the basis of the data given in Table 5 and Eqs. (17-25), it is possible to determine the absolute values of the compressed-gas losses for different types of insulation and their distribution over time. The total and hourly amounts of heat fed to the liquid during the cooling process are presented graphically in Fig. 8 for different types of insulation. The heat drawn off from the inner half-layer of insulation and from the vessel is associated with the initial cooling period.

Table 5

Balance Table

air m³	$A_{\text{cyl}}$	$A_{\text{sp}}$	$A_{\text{tank}} - A_{\text{cyl}}$ sp	$B_{\text{cyl}}$	$B_{\text{sp}}$	$B_{\text{tank}} - B_{\text{cyl}}$ sp	$C_{\text{cyl}}$	$C_{\text{sp}}$	$C_{\text{tank}} - C_{\text{cyl}}$ + C sp	$C_{\text{tank}} - A_{\text{tank}}$ + B tank	Deviation %
0-1	62.3	68.8	131.1	0.0	0.0	0.0	68.0	68.5	136.5	131.1	-4.0
0-2	96.5	96.0	192.5	0.0	0.0	0.0	102.5	107.5	210.0	197.5	-8.3
0-3	135.5	140.0	275.5	0.0	0.0	0.0	137.0	139.0	276.0	275.5	0.0
0-4	161.0	167.5	328.5	0.0	0.0	0.0	163.0	166.0	329.0	328.5	0.0
0-5	187.0	193.5	380.5	0.0	0.0	0.0	189.0	193.0	382.0	380.5	-1.0
5-10	94.5	100.0	205.5	0.0	0.0	0.0	101.0	104.8	205.8	203.5	-1.0
10-20	146.5	150.0	296.5	10.6	12.6	22.2	149.0	156.7	305.7	319.7	+4.3
20-30	62.5	94.5	177.0	36.4	37.2	73.6	117.5	125.9	243.4	250.6	+2.9
30-40	44.6	47.4	92.0	51.5	56.6	108.1	101.4	110.0	211.4	200.1	-5.3
40-50	29.8	34.4	64.2	65.4	69.0	129.0	92.0	101.5	193.5	193.2	0.0
50-60	19.0	21.4	40.4	70.7	76.0	141.4	87.0	85.6	182.6	181.8	-0.4
60-70	10.6	12.6	23.2	72.5	80.6	151.3	83.0	92.0	173.0	174.5	+0.87
70-80	6.57	6.3	12.9	73.7	83.5	156.0	81.0	90.4	167.4	168.9	+1.48
80-90	3.83	3.74	7.6	74.3	84.5	159.2	80.0	86.5	165.5	165.8	+0.42
90-100	3.06	2.14	5.2	74.6	85.5	159.8	79.0	86.2	165.2	165.0	-0.1
100-110	2.81	2.03	4.8	74.7	86.7	161.1	77.0	86.2	163.9	165.9	+1.2
110-120	2.34	1.76	4.1	74.7	86.7	161.4	77.0	86.2	163.2	165.5	+1.4

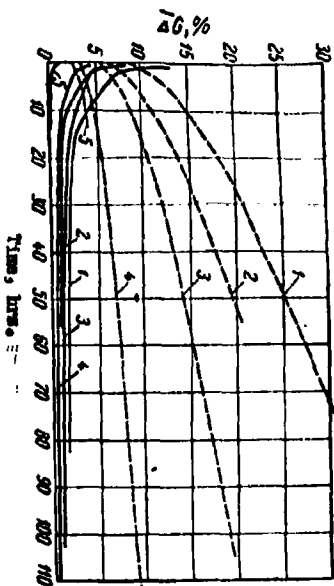


Fig. 8. Variation of hourly and total cold losses with time in an oxygen cylinder for various types of insulation in percentages of the capacity of the cylinder (solid curves - hourly losses; dotted lines - total losses): 1) magnesium ( $\gamma = 400 \text{ kg/m}^3$ ); 2) mineral wool; 3) total losses; 4) aerogel; 5) mpor.

An analysis of the graph shows that the greater the density and specific heat of the insulation, the more the liquid expended in cooling it and the longer the duration of this process. Thus for oxygen with magnesia insulation ( $\gamma = 400 \text{ kg/m}^3$ ) the cooling is only completed in 83 hrs, while for mipor it is completed within 13.5 hrs.

Steady-state Stage. During steady state the heat flow passing through any layer of insulation is constant. It may be calculated in accordance with the temperature field of any layer or in accordance with the boundary conditions of the entire tank as a whole. The calculation for the cylindrical portion of the tank may be made using Eq. (8).

$$Q_{st} = \frac{2\pi\lambda L}{2.31g \frac{R_{ex}}{R_{in}}} (t_x - t_n)$$

Substituting appropriate radius and temperature values, we obtain:

$$\text{for oxygen} \quad Q_{st}^{O_2} = 9400\lambda \quad (26a)$$

$$\text{for nitrogen} \quad Q_{st}^{N_2} = 10000\lambda \quad (26b)$$

$$\text{for hydrogen} \quad Q_{st}^{H_2} = 12600\lambda \quad (26c)$$

where  $\lambda$  is the coefficient of thermal conductivity of the insulation, kcal/m·hr·°C.

Using Eq. (10) for the spherical portion of the tank, we obtain

$$Q_{st} = \frac{4\pi\lambda (t_x - t_n)}{\Delta R} R_{ex} R_{in}$$

Substituting the values, we obtain

$$\text{for oxygen} \quad Q_{st}^{O_2} = 10700\lambda \quad (27a)$$

$$\text{for nitrogen} \quad Q_{st}^{N_2} = 11400\lambda \quad (27b)$$

$$\text{for hydrogen} \quad Q_{st}^{H_2} = 14400\lambda \quad (27c)$$

Thus we have for the tank as a whole

$$\text{for oxygen} \quad Q_{st}^{oyl} = 9400\lambda + 10700\lambda = 20100\lambda \quad (28a)$$

$$\text{for nitrogen} \quad Q_{st}^{oyl} = 21400\lambda \quad (28b)$$

$$\text{for hydrogen} \quad Q_{st}^{oyl} = 27000\lambda \quad (28c)$$

For a tank capacity of about 11,200 liters the losses of liquid oxygen per hour for various types of insulation are: for mipor 0.093%; for aerogel, 0.0375%; for mineral wool, 0.188%. The losses of hydrogen will be equal, respectively, to 0.94%, 0.38%, and 1.88% per hour, i.e., an order of magnitude greater than in the case of oxygen.

Taking into account that during the period of intense losses it is inexpedient to collect the vaporizing gas for subsequent use, the filled tank should be kept at the factory where it was filled for a certain length of time before being forwarded.



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